Practical Advice for Teaching Inquiry-Based Science Process Skills in the Biological Sciences

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Practical Advice for Teaching Inquiry-Based Science Process Skills in the Biological Sciences

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Inquiry learning is student-based exploration of an authentic problem using the processes and tools of the discipline. Often inquiry learning is presented in a fashion that mirrors the scientific method, proceeding from identification of a problem to reporting of findings. In post-secondary settings, these scientific-method inquiry exercises typically serve as the primary source of science process skill development. There is, however, a major shortcoming to this approach. Inquiry is used to teach science process skills, yet science process skills are the tools by which inquiry is conducted. How can we expect our students to be successful learning by inquiry if we have not provisioned them with the required skills? Instructors should not make the mistake of assuming that all students possess the science process skills required to conduct a full scale inquiry investigation. We have seen in our classes that many students lack the skills necessary to conduct scientific inquiry even at the most simplistic level. When inquiry learning is presented as a complete sequence from problem to conclusions, students, regardless of the number of process skills mastered, will only be as strong as their weakest link. For example, a student may do a wonderful job of analyzing data, but if his/her experimental design is flawed, the data generated will be flawed as well, and conclusions based on incorrect data will be inaccurate. Individual science process skills must be developed before one can proceed to full scale investigations.

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Specific science process skills (Table 1) can be individually targeted and developed by focusing on a single component of scientific inquiry. This provides instructors with the advantage of teaching a skill without employing an entire scientific-method inquiry exercise. This allows a greater variety of individual skills to be taught and can ensure that more students obtain mastery of them. Additionally, because the science process skill development strategies are more narrowly defined than most inquiry learning strategies, they can be designed with specific student interests in mind. For example, since experimental design process skills can be developed independent of other components of the scientific method, a student interested in orangutan behavior can design the study without actually implementing it. Thus, process skill learning becomes a personalized and meaningful experience. Routine use of these strategies offers students multiple opportunities to practice and refine their skills, providing them with a solid foundation for conducting more advanced inquiry techniques or investigations on their own in the future.

An additional benefit of teaching specific process skills independently includes overcoming time restrictions and assessment issues that often deter instructors from using intensive inquiry-based techniques. Due to the focused nature of these activities, both preparation and implementation time is less demanding than with most inquiry learning. In addition, teaching of individual process skills requires less extensive resources than involved inquiry designs. Another key strength of teaching process skills independently is that they can be tightly interwoven with the subject matter. When using these activities, students should make observations, formulate hypotheses, critique experimental designs, analyze data, make predictions, draw conclusions, etc. relevant to the concept(s) being taught. Process skills should be a means for covering the content, not an exception or addition to it. Because most inquiry lessons are complex, large-scale assignments, they typically result in a lengthy research report that serves as the primary point of assessment. This strategy, in addition to requiring hours for grading the reports, regretfully provides the greatest feedback after the fact. Assessment should be a continuous cycle of feedback between student and instructor, allowing each to monitor and adjust a student's learning (see Straits & Wilke, 2002). This type of focused, immediate feedback is possible with the instruction of specific, narrowly-defined process skills. Additionally, because teaching individual skills requires relatively little time and effort, process skill lessons can serve as a source of feedback without necessarily being graded. Teaching single process skills, separate from the scientific method, allows students to learn science content while developing their ability to conduct scientific investigations in an effective and efficient manner.

TABLE 1.
Common tools of science: knowledge and skills necessary to conduct scientific inquiry.

FACTUAL INFORMATION	Discipline-specific content knowledge
GENERAL PROCESS SKILLS	Observing, classifying, designing, drawing, writing, measuring, predicting, inferring, analyzing, applying, summarizing, communicating, evaluating, synthesizing, creating, problem-solving, etc.
SCIENTIFIC METHOD SKILLS	Asking questions, proposing hypotheses, making predictions, designing experiments, collecting & analyzing data, drawing conclusions, interpreting evidence, building models, making judgements, etc.
EXPERIMENTAL DESIGN SKILLS	Identifying: sources of error, variables (control/dependent/independent), appropriate materials, limitations, etc.

The following activities have been developed to provide initial ideas for educators interested in incorporating process skill instruction into their teaching practice.[1] Originally intended to promote active learning in the classroom, the activities have been modified to reflect the various components of scientific inquiry (i.e., science process skills). Because they are based on the same theoretical principles as other inquiry techniques, these strategies (used to introduce, spark interest in, and advance knowledge of several different topics), have many of the same benefits (see Table 2). In short they have the potential for providing a solid background of science process skills through meaningful learning experiences. They also give students a sense of ownership and relevance that makes that knowledge more valuable and promotes confidence in their ability to do science. By developing science process skills continuously over time, students can obtain the background knowledge, confidence, and direction needed to conduct inquiry at an advanced level.

[1] We are advocates for inquiry learning and are offering these more focused activities not as a replacement for true inquiry, but as a complement to it. Also, for the instructor unfamiliar with inquiry learning, these focused activities may be a less intimidating means for beginning to incorporate inquiry into his/her teaching practice.

TABLE 2.
Advantages of inquiry learning include active, meaningful, and higher-level learning. Specific benefits (adapted from Svinicki, 1998) are listed for each.

INQUIRY LEARNING INVOLVES ACTIVE LEARNING THAT:
- increases attention to task(s).
- focuses attention on critical variables.
- is more motivating than passivity.
- forces construction of a response as opposed to simple recognition.
- produces early and frequent feedback.
- creates an episodic memory from which to reconstruct knowledge.

INQUIRY LEARNING RESULTS IN MORE MEANINGFUL LEARNING THAT:
- makes use of personal associations.
- involves deeper processing of ideas.
- involves confronting misconceptions.
- is often more concrete initially.
- occurs in an authentic context.

INQUIRY LEARNING ENCOURAGES HIGHER LEVEL LEARNING SUCH AS:
- viewing the discipline as a dynamic process, not simply a static set of facts to memorize.
- developing a set of problem-solving strategies for tackling the unfamiliar.
- encouraging a belief in one's ability to learn about the subject.
- accepting responsibility for one's own learning (self-regulated learners).

Simple Classroom Activities

Activities provided in the Science Process Skill Development Guide (Table 3) vary in duration, complexity, and degree of interaction required between teacher and student. However, most are simple to perform, require little class time, and can be incorporated readily into a traditional lecture setting regardless of class size. Furthermore, the activities can easily be modified to suit individual instructor's course goals, objectives, and teaching style without restricting content coverage. In general, most of the activities are based on a teaching approach in which the instructor provides a relevant prompt such as a question, set of observations, data, etc., while the students use science process skills to generate an appropriate response. Specific examples include providing students journal articles with sections (e.g., Hypotheses, Materials, Conclusions) omitted and asking them to provide the omitted section; providing students with an ethical consideration or science-related controversy and asking them to provide opinions, solutions, questions, and/or contrasting points of view; and providing students with a lab protocol and asking them to provide safety procedures. Modifying this relatively simple protocol allows the instructor to create multiple and varied opportunities for students to develop their science process skills. The flexibility of these activities allow their use in a wide range of settings, developing science process skills concurrent with acquiring content knowledge. Specific examples of each strategy are listed in the Appendix.

Engagement Activities

Engagement activities are traditionally used to organize in advance the day's lecture topic. They serve to access student prior knowledge, identify misconceptions, and get students thinking about the subject matter to be covered. Examples of typical engagement activities include, but are not limited to: playing a song relevant to the topic of the day, reciting a humorous anecdote, stating a controversy within the field, displaying relevant cartoons, showing a demonstration, reading student- or teacher-generated questions, and reading relevant news or journal articles.

Modified to reflect authentic science situations and incorporate greater student involvement, engagement activities can develop science process skills. During an inquiry-based engagement activity, students produce a question or a problem (actual or hypothetical) based on the information given, propose answers to controversial questions or solutions to problems in the field, interpret and apply information in another setting, propose an analogous situation, apply conceptual information, list observations, propose causal explanations, make predictions, design experiments, or draw conclusions based on the initial prompt. Student responses can be given orally or in writing and can be generated individually or within collaborative groups. The instructor should then tie in student responses generated by the engagement activity to the day's topic via lecture, class discussion, or other methods. Engagement activities can also be used at the end of class in anticipation of the next meeting.

Minute Papers

Popularized by Angelo and Cross (1993), this strategy has the lecture punctuated with short writing assignments that typically take "only a minute" to do. Minute papers serve to review material, evaluate comprehension, or uncover misconceptions. Often they are used in succession to reveal student gains in content knowledge. They may even set the stage for

TABLE 3.
Science Process Skill Development Guide. Instructional protocol for designing process skill activities in which the instructor provides a relevant prompt and students generate an appropriate response.

INSTRUCTOR PROVIDES	STUDENTS GENERATE
problem—modern or historical	solutions, alternative answers, analogies
situation, scenario	parallels to topics previously studied or their own prior knowledge
interesting photos or scenario	a list of observations and/or questions
set(s) of observations	questions, hypotheses, inferences
observations or experimental designs of various quality	a critique which identifies strengths and/or flaws
ethical consideration/science-related controversy	opinions, solutions, questions, contrasting points of view
hypothetical or actual model	a critical analysis of the model
lab protocol	safety procedures
actual journal articles with sections omitted	omitted sections (i.e., hypotheses, materials, experimental design, data, conclusions, etc.)
questions	hypotheses
hypotheses	predictions, experimental design, variables (independent, dependent, and control)
experimental design	predictions, variables, flaws/biases, and/or limitations
experimental data/results	an analysis of the data and/or conclusions, a summary of the results and/or a graphical representation (i.e., charts, graphs, tables)
conclusions	logical topics/hypotheses for further study
a group of objects	a dichotomous key, a classification scheme/matrix
an article from a scientific journal	an abstract (then compare to actual abstract), a summary of strengths and weaknesses, an evaluation of its scientific accuracy and validity, a critical review of the literature cited
science articles from newspapers or popular magazine articles	an evaluation of their scientific accuracy and validity, a review of the literature cited
experimental design	hypotheses and/or questions that could be addressed by experiment
results	hypotheses and/or experimental design that could yield results
predictions	hypotheses that might stem from predictions
journal articles with sections of experimental design omitted	appropriate experimental design

upcoming lectures or class discussions. Typical minute papers, which emphasize content, ask students to summarize the points of a day's lecture, describe the most confusing topic, or write three exam questions based on the day's lecture material. To begin, the instructor poses a question to the class. These instructor-generated questions encourage students to think about what they have learned. The students, working independently, in pairs, or in groups, record their responses on a piece of paper or note card. The instructor then collects the papers for review after the class is over. A quick perusal can verify students' understanding, as well as reveal misconceptions to be addressed in the next class period.

Minute papers can also serve as an opportunity to develop science process skills. Activities that ask students to write an interesting research question; formulate hypotheses; record observations; analyze information from photos, abstracts or graphs; offer ideas or solutions to questions or problems; generate hypotheses, inferences, predictions, or conclusions; or analyze information presented during class can develop process skills and take only a minute or so. Minute papers are of great value because they give students a chance to reflect on what they are learning *while* they are learning and offer those who may be reluctant to ask questions in class a chance to get feedback from the instructor. Additionally, when used in succession they provide insight to the progress in process skill development (e.g., refinement of hypotheses or research questions, greater detail in observations, more sophisticated classification schemes, etc).

Think-Pair-Share Activities

There are many derivations of think-pair-share activities, but a common procedure has students work independently, thinking about a problem and recording a solution. Then students working in pairs discuss the problem and improve their solutions based on the input of their partners. The instructor harvests responses from the class and then reviews the responses with the class as a whole. This procedure allows students to share in the responsibility of an answer, reducing fear and intimidation students may feel particularly in a large class. Additionally, cooperative learning has been shown to be a beneficial source of student feedback (Johnson, Johnson, & Smith, 1998), contributing to increased student achievement (Albanese & Mitchell, 1993).

Think-pair-share activities lend themselves well to the development of science process skills. Discipline-specific, higher cognitive-level questions are especially useful in this activity. Those that require the application of previous knowledge, the formation of appropriate hypotheses, the designing of procedures that would test a hypothesis, or the analysis of actual data can lead to greater student involvement and understanding of the science content and processes being taught. To use the think-pair-share strategy for science process skill development, instructors can write a question on the board, show an unusual scene in nature, provide an outside journal article, or any of the engagement activities mentioned above. Students can then learn from and practice with each other, improving their science process skills and coming to understand science as a collaborative venture. Although it requires more class time than the techniques described earlier, it is still a relatively time-efficient method for developing science process skills.

TABLE 4.
Science Process Skills Lecture adapted from Johnson, Johnson, and Smith, 1998.

INSTRUCTIONAL COMPONENT	TIME REQUIREMENT
Process skills engagement activity	5 minutes
Initial lecture segment	15-20 minutes
Process skills activity	5-10 minutes
Second lecture segment	10-20 minutes
Process skills activity	5-10 minutes
Summary and/or Evaluation	10 minutes
Total Time	50-75 minutes

Science Process Skills Lecture

Finally, the activities described above can be combined with lecturing and incorporated into an instructional model useful in the college science classroom. This instructional model (Table 4), adapted from Johnson, Johnson, and Smith (1998), begins with an initial engagement activity designed to briefly introduce students to content and/or process skills. Following the introduction, the instructor lectures on content relevant to the initial engagement activity. After the lecture segment, students participate in an activity designed to complement the lecture material. This gives students the opportunity to develop a science process skill based on the lecture material just presented, while developing or reinforcing content knowledge. The instructor then delivers the second segment of lecture which is followed by another process skill activity focusing on the second lecture segment. This can be a continuation of the first activity or a totally new one emphasizing a different process skill. The final segment of this model allows the instructor to provide students with a summary of the important points or, better yet, initiate activities where students are asked to think about and reflect on the content and process skills they have just experienced. Summary activities may include the more traditional uses of the minute papers or think-pair-share activities mentioned above or even a short quiz. Incorporating the traditional applications of these activities allows quick assessment of whether students have reached the instructional objective(s) or further instruction is necessary. The model is easy to implement, has the benefit of structuring class time, and integrates science content with science process skills.

Conclusion

Teaching specific process skills independently overcomes the difficulties that often deter instructors from implementing intensive inquiry-based techniques. Due to the focused nature of the activities presented here, preparation and implementation times are much less consuming than "true" inquiry learning and may require fewer resources. Instructors have the advantage of focusing on one or a few science process skills at time. Therefore, an entire inquiry lesson does not have to be employed each time a specific science process skill is taught.

There are many potential benefits for teaching process skills independently. However, the greatest benefit is that routine teaching of these skills increases the likelihood that students will learn the skills. Students with stronger foundations in science process skills will be able to use them in other more intensive scientific inquiries, and are more likely to be successful in those inquiries. For this reason, instructors should emphasize the teaching and reinforcing of science process skills.

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Appendix

Engagement Activities

These activities serve to organize in advance the day's topic. They are designed to access students' prior knowledge, identify misconceptions, and get student thinking about the subject matter to be covered.

With traditional engagement activities, the instructor:

- plays a song relevant to the topical material of the day.
- recites a humorous anecdote relevant to the material.
- displays relevant cartoons, pictures, or videos.
- shows a demonstration or experiment.
- reads or displays relevant news or journal articles.

Inquiry-based engagement activities teach science process skills by beginning with the traditional activities mentioned above and then asking students to:

- produce a question or problem (actual or hypothetical) based on supplied information.
- propose answers to controversial questions or solutions to problems in the field.
- interpret and apply information in another setting.
- propose an analogous situation to a scientific concept.
- list observations, propose causal explanations, make predictions, design an experiment, or draw conclusions based on the engagement activity.

Examples from Biology

In our classes we project an unusual picture using an overhead and ask students to generate questions, hypotheses, predictions, or explanations based on what they see. For example:

- We use a picture of a tree with no vegetation underneath it and propose a question, such as, "Why is there no vegetation underneath the tree?" Ask students to propose hypotheses, make predictions, and design experiments that would test them. We then discuss any number of topics, such as photosynthesis, competition among plants, allelopathy, symbiosis, etc.

- In another example, we display pictures of a bee, wasp, and a fly that all show warning coloration and ask students to record their observations and propose explanations for the similarities. We then proceed with lessons on Mullerian and Batesian mimicry.

After each initial activity, one can then launch into a discussion of the concepts. The students benefit from the practice of these science process skills that are easily assessed in short segments. We can address "good" versus "bad" hypotheses, predictions, etc. in the next class meeting.

Minute Papers

These activities serve to help students think about, apply, and reflect on what they have learned and typically only take "about a minute or so" to implement. An advantageous component of this strategy is that the engagement activities listed above can also be used as the bases for minute papers either before, during, or after instruction. Modified from their traditional use, minute papers offer a quick and easy way for students to develop their science process skills.

Traditional minute papers, which emphasize content, ask students to:

- summarize the main points of today's lecture in three sentences or less.
- describe the most confusing topic of today's lecture, being as specific as possible.
- write three test questions based on today's lecture material.

Inquiry-based minute papers, which emphasize science process skills, ask students to:

- record observations and analyze information from photos, abstracts, data tables, graphs, or short demonstrations.
- generate hypotheses or inferences
- make predictions or draw conclusions
- offer ideas or solutions to questions or problems.
- apply and/or summarize information

Example from Biology

In human physiology courses we often have our students make predictions and provide explanations to various problems. For example, after a discussion on the conduction pathway of the heart and EKGs, we will ask students to propose a hypothesis and predict what would happen if the signal were blocked from traveling down the left bundle branch. We even ask them to draw an EKG to reflect this. The students record their answers on index cards that they turn in at the end of class. We can then quickly assess students' responses at a later time and address any misconceptions in the next class. This activity has two primary benefits: it requires higher-order thinking skills (students must apply content information to solve a problem) and it emphasizes several science process skills (e.g., hypothesis generation, prediction making, and applying factual knowledge).

Think-Pair-Share Activities

These activities are collaborative efforts that encourage students to develop, communicate, explore, and critically reflect upon ideas about a given topic. Engagement activities and minute papers can serve as the basis for think-pair-share activities.

The traditional sequence of think-pair-share activities begins with the presentation of a problem, scenario, question, etc. Students think and record responses individually and subsequently pair up to discuss (for several minutes) an appropriate answer to a question or problem posed by the instructor or another student. The student pairs can then modify their answer(s) based on each other's input. The instructor harvests responses from the class and then goes over the responses with the class as a whole.

Inquiry-based sequence of think-pair-share activities emphasizes science process skills. This procedure can be modified to reflect varying degrees of student interaction and inquiry. Discipline-specific, process-based questions of higher cognitive levels (e.g., questions that require applying prior knowledge, developing appropriate hypotheses, designing procedures to test a hypothesis, analyzing actual data, or drawing conclusions) are especially useful and can lead to greater student involvement and understanding of the material and the processes being conveyed.

Examples from Biology

In our human physiology course we provide students with actual experimental data and have them analyze it independently. They then share their thoughts with their neighbors and with the entire class. For example, we give students glucose tolerance test data and ask them to create a graph and record their conclusions based on the data. We then ask them to pair up and compare their work with a classmate. As a class, we discuss the students' conclusions and then lead into a discussion of hormonal influences on blood glucose regulation.

When we teach evolution, we provide students with data that Darwin collected, without mentioning his name or the word evolution, in the context of a "recent" study. We ask students to record their own conclusions based on these data and share their thoughts with a neighbor. We then harvest responses. Some, often many, students draw the same conclusions as Darwin. Since this approach allows students to form their own conclusions based on actual data, students are more open to considering Darwinian Evolution and viewing this theory as an interpretation of data, consistent with other aspects of the course. It also allows the application of science process skills to function as the means for understanding the content presented.